A Novel Conceptual Design on Robotic Bone-Cutting Device Based on Kinematic Analysis: Toward Development of A Novel Robot-Assisted Total Knee Replacement Surgical System

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Abstract— **Total knee replacement surgery (TKR) is one of the most frequent orthopedic operations. The TKR surgeon requires bone cutting and surfacing processes at the femur and tibia bone to fit with the certain trigonometric shape of knee implants. In the traditional TKR procedure, several handheld cutting jigs are used with the vibrated saw. Therefore, the TKR surgery requires skilful surgeon and health care personals to perform a nice output surgery. Our study aims to develop a robotic bone-cutting device which has minimum degree-of-freedom (DOF) to perform the bone cutting and surfacing tasks instead of using specific jigs and unstable saw. The new design is based on our kinematic analysis on the bone shape which directly related to the knee implants. Therefore, the design is on using only 4 possible simple motions of cutting device to create the suitable shapes, these motions are (1) Tool rotate about a single axis, (2) Tool slide in and out for adjusting the depth of planes, (3) and (4) are for plane creating in similar way as an X-Y table motions. The study has delivered a novel design of the 4-DOF robotic bone-cutting device based on the tool rotation around the distal of bone as the 1st DOF, the tool sliding in and out as the 2nd DOF, and the tool motion on a plane as the 3rd and 4th DOFs. A full detail of study is described. A prototyped hardware is developed and validated on a series of phantom based demonstrations. The project is working toward the full development of a novel robot-assisted TKR surgical system.**

Keywords-component; Total Knee Replacement, Surgical Robot, Bone Cutting, Bone Surfacing, Medical Robotics

I. Introduction

A. Motivation

Nowadays, the numbers of robotic applications are introduced in surgical works to increase the operating performance. Orthopaedics is one of the areas that medical robots are introduced. From ergonomic point of view, orthopaedic surgery has a large room to improve. Firstly, low-tech tools as hand drill and oscillating saw are used [1]. Secondly, it is lacked of the high accuracy guidance can guide surgeons cut the bone into the specific shape [2]. And the surgeon has human physical limits which tactile sensitivity and prone to tremor and fatigue [3]. These problems could be solved by applying robotic system to surgical procedures.

From the studied of prevalence of osteoarthritis has shown that the most problems for Asian was about knee joint [4]. The worst knee joint disease is to remove all surfaces of distal femur and proximal tibia that call Total knee replacement surgery (TKR).

B. Background and Related Work

For knee joint has composed of 4 components, including femur, patellar, tibia and fibula. Femur and tibia bear the weight of the body while patella and fibula are supporting parts for the mobility.

Total knee replacement surgery is the procedure to resurface the femur and tibia and attach the prosthetic component to the bone. The femoral component is placed on the distal femur and another is placed on the proximal tibia. To do this, six planes and two holes are needed. The good alignment and relationship of the planes to the prosthetic component are required to regain the function of the knee joint. It is essential for the patients with osteoarthritis, rheumatoid arthritis, or other degenerative joint diseases and defects to be treated by total knee replacement surgery. [3]

The conventional method for total knee replacement surgery is call jig-based system. First, the surgeon performs preoperative planning from CT or X-ray image. Then, a seven to ten inch incision is made for the surgeon to be able to access the joint. In a conventional method, the specialized jigs or resection guide are used to guide the surgeon to cut the bone. [5] Jig-based procedure has some disadvantages because several jigs are used sequentially so an alignment error is accumulated and moreover, the universal jig is not fit specifically to any individual patient's bone. The developed robot for total knee replacement is able to overcome the problem of the conventional method. [2]

To nicely achieve these procedures, some of the robotic system has been present to improve the accuracy of the operation. For example, Acrobot used the hand-on concept and the active constraint concept is applied in the system, which composed of 6 degree-of-freedom (DOF) positioning arm and 3-DOF on the active site [6-9]. The next example firstly developed for total hip replacement surgery and then applied to knee surgery is ROBODOC [10, 11]. It used SCARA manipulator and the cutter drive is installed at the end effecter of the robot arm, while the robot works automatically according to pre-defined task from ORTHODOC[12]. Another example is 5-DOF active robot

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which resects bone either automatic mode or semiautomatic under control by the surgeon [5, 9].

Our robot-assist total knee replacement surgical system in this paper will purpose the simplest way to design robot base on kinematic of total knee replacement procedures.

C. System Overview in Our Robot-Assisted Total Knee Replacement Surgical System

For this purposed robotic system consist of TKR navigation system, TKR feedback system and robot-assist TKR surgical system (as depicted in a diagram on Figure 1).

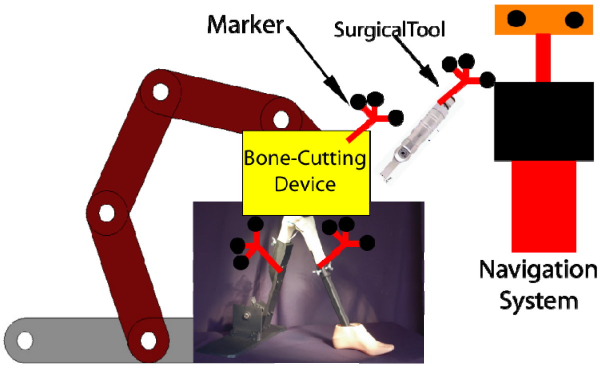

Figure 1. System Overview in Our Robot-Assisted Total Knee Replacement Surgical System

About navigation system for robot-assist total knee replacement surgical system will be based on optical navigation system which matches bone data from pre-operative plan with patient bone in intra-operative. During the operation, stereo camera will track markers that place on surgical tool, robot, and patient’s bone and then calculate position and orientation for whole system. It can guide the robot to the right position.

Robot-assisted TKR surgical system consist of 2 main parts, the first part is robot arm which bring bone-cutting device to surgical area, and bone-cutting device is connected at the end of robot arm. This part is in contact with patient.

This paper will focus on bone-cutting device.

II. Kinematic Analysis on Total Knee Replacement Procedures

Kinematic of bone-cutting device have been considered from total knee replacement procedure and based on physical characteristic of prosthetic component that will be described on this session.

A. Bone Cut on Femur

Most of femoral prosthesis model is designed as a plane and holes (as shown in Figure 2). The model was designed as geometric shape. Considering characteristics of each plane will move on the same circular motion but in various angle and distance between plane to center of motion that show in Figure 3.

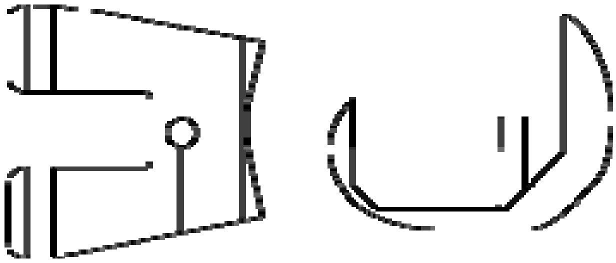

Figure 2. Sketch of femoral prosthesis (Redrawn from [6])

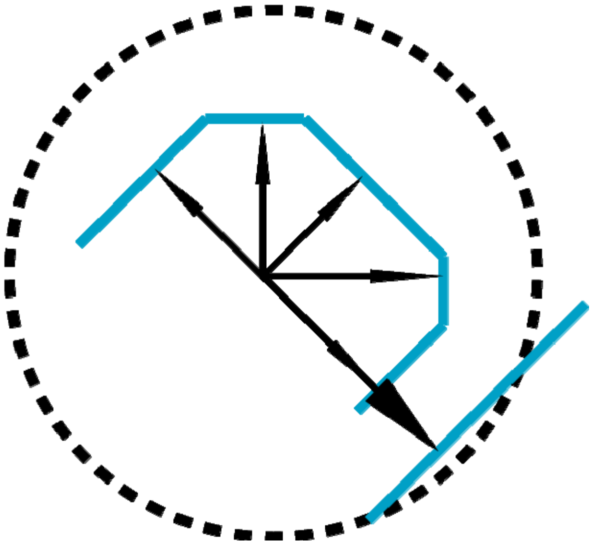

Figure 3. Sketch planes on knee prosthesis

B. Bone Cut on Tibia

For tibia prosthesis, one plane and hole is required (as shown in Figure 4).

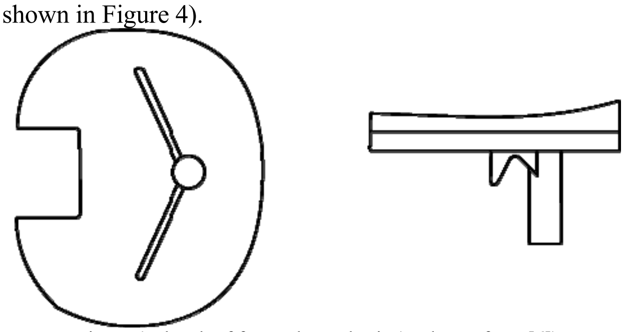

Figure 4. sketch of femoral prosthesis (Redrawn from [6])

After kinematic of TKR procedure has been analyzed. The next step is to generate the conceptual design for bone-cutting device.

III. Design of Robotic Bone Cutting Device

The architecture of bone-cutting will be based on the kinematic of knee prosthesis which was mentioned above.

A. Design Requirement

The bone-cutting device is developed initially aimed at total knee replacement. The task of the bone-cutting device is typically bone machining by using high speed rotary cutter to cut the bone to a specific shape. The work space of the robot can be pre-programmed to avoid the critical area such as ligament.

Furthermore, in order to be introduced to the surgical procedure, the proposed robot should be satisfied these following requirements [13].

- The device must be safety concerned. It must be safe for the surgeon, the patient and medical staff in crowed environment.
- The part of the device that contact to the surgeon, patient or the sterile area must be able to be made sterile.
- The accuracy level of the device must be sufficient. For orthopaedic task, the error from the system must be less than 1 mm.
- The device has to be ergonomically designed. The surgeon must be able to operate the device comfortably. Moreover, to be located in the operating room, the robot must be fit well with the surgical environment and must not obstruct the work of the surgeon and medical staff [13].

From this session above are general requirements for medical robot. Moreover, the specific requirement for each work should be required.

- The bone-cutting device has to resurface follow the kinematic analysis of TKR surgery.
- The bone- cutting device should have a proper DOF.

B. Conceptual Design

Concept of bone-cutting device will base on kinematic on TKR procedures. It will be described on this session.

Figure 5. 1 DOF of rotation

For multiple planes, circular motion is needed to change the direction from reference plane to another plane.

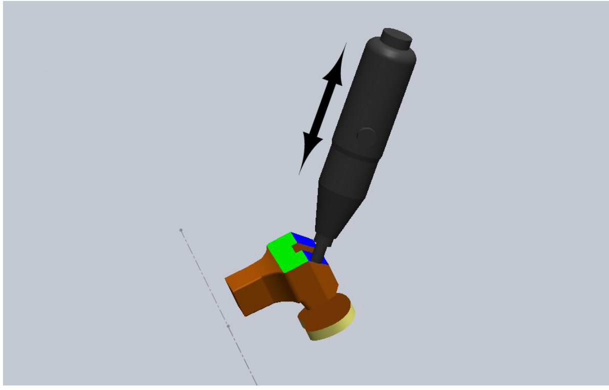

Figure 6. 1 DOF in translation for adjust the length from bone

From Figure 3, to adjust the distance between plane and center of the circular motion the bone cutting device needs 1 DOF of translation to adjust the distance of each plane.

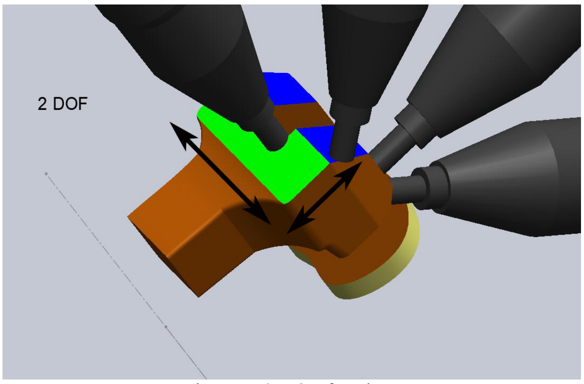

Figure 7. 2 DOF for plane

For a single plane, 2 DOF of translation motion could generate a plane.

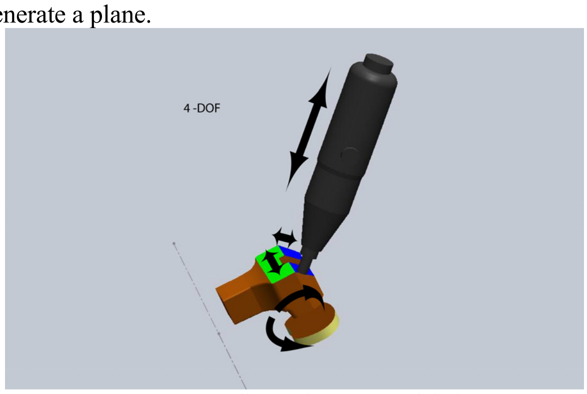

Figure 8. Overall DOF for conceptual design

The conceptual design of a bone-cutting should have at least base on kinematic analysis.

C. Preliminary Design

In Figure 9, preliminary design of bone cutting device under condition of the conceptual design in previous session.

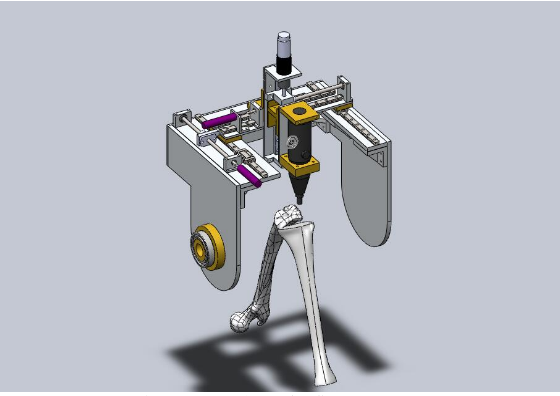

Figure 9. Design of a first prototype

The CAD-design of bone cutting device has 3-DOF of translation attached to ball screw and linear slide. The ball screw is driven by encoded DC brushed motor with gear head. This will not harm patient when electricity was out. For circular motion, the rotation of motion will be design by using belt-driven mechanism and limited the range of motion about 180 degree. In rotation joint will install mechanical locking device to prevent the patient when the electricity is out and easy to move the device out from patient.

IV. SIMULATION OF ROBOTIC BONE-CUTTING DEVICE ON TOTAL KNEE REPLACEMENT

This session study about the kinematic of bone-cutting device on MATLAB.

$$P'_{ee} = [R(\varnothing)T(x)T(y)T(z)](P_{org})$$

$$P'_{ee} = {}^1_0H(P_0)$$

From the equation of motion in term of homogeneous transformation, the equation is just 1 matrix cover all motion of bone-cutting.

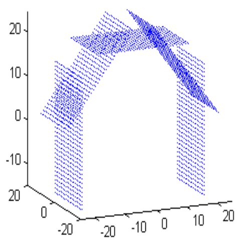

Figure 10. Work space of a bone-cutting device

In Figure 10, Show the work space of bone- cutting device which base on kinematic analysis

V. CONCLUSION

Our paper presents a study in designing a novel 4-DOF robotic bone-cutting tool to be used in the robot-assisted TKR surgical system. The design is based on the kinematic analysis of the traditional TKR procedures and its knee implants' trigonometric shapes. A set of simulation results from designed prototype robotic bone-cutting tool has shown a satisfied outcome. The project is working toward the full development of a novel robot-assisted TKR surgical system.

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